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Original article

Condition assessment and preservation of open-air rock art panels during environmental change

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ABSTRACT

Thousands of Neolithic and Bronze Age open-air rock art panels exist across the countryside in northern England. However, desecration, pollution, and other factors are threatening the survival of these iconic stone monuments. Evidence suggest that rates of panel deterioration may be increasing, although it is not clear whether this is due to local factors or wider environmental influences accelerated by environmental change. To examine this question, 18 rock art panels with varied art motifs were studied at two major panel locations at Lordenshaw and Weetwood Moor in Northumberland. A condition assessment tool was used to first quantify the level of deterioration of each panel (called “staging”). Stage estimates then were compared statistically with 27 geochemical and physical descriptors of local environments, such as soil moisture, salinity, pH, lichen coverage, soil anions and cation levels, and panel orientation, slope, and standing height. In parallel, climate modelling was performed using UKCP09 to assess how projected climatic conditions (to 2099) might affect the environmental descriptors most correlated with elevated stone deterioration. Only two descriptors significantly correlated ($P < 0.05$) with increased stage: the standing height of the panel and the exchangeable cation content of the local soils, although moisture conditions also were potentially influential at some panels. Climate modelling predicts warming temperatures, more seasonally variable precipitation, and increased wind speeds, which hint stone deterioration could accelerate in the future due to increased physiochemical weathering. We recommend key panels be targeted for immediate management intervention, focusing on reducing wind exposures, improving site drainage, and potentially immobilizing soil salts.

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1. Research aims

Open-air rock art stone panels exist around the world; however, growing evidence indicates such panels are rapidly deteriorating due to natural and anthropogenic causes [1] and we now see only a small fraction of what once existed [2]. As such, remaining panels are of special importance for preserving tangible links to our distant past. Unfortunately, processes that influence deterioration of exposed panels are not well understood, especially relative to preservation and management [3]. Stone is not immutable, but because of perceptions otherwise, rock art has received less direct conservation attention than other archaeological materials [4]. Change and decay are innate to all stone [5]. Therefore, delineating factors that influence stone deterioration is critical, especially

with prospective environmental change [6–9]. In reality, rock art management largely has focused on controlling public access with less attention has been placed on protection against stone weathering from an eco-environmental perspective [10,11]. As such, we assessed 27 geochemical and physical descriptors around 18 open-air rock art panels across Northumberland in Northern England to compare current panel conditions with present (and past) local environments to develop more science-informed approaches for managing these monuments into the future.

2. Introduction

Rock art is one of the earliest forms of artistic expression, with some sites being more than 50,000 years old [12]. This art is either found as pictographs (paintings) or petroglyphs (engravings and carvings) on natural rock surfaces (boulders, cliffs, cave walls, etc.) with motifs ranging from animal forms to geometric shapes like circles, spirals, hollows, and lines. Although such art often has been ignored [13], studies are now increasing due to a growing awareness of their social and historic significance [14–18].

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Fig. 1. Example rock art panels located in northern England at Lordenshaw and Weetwood Moor, Northumberland.

Neolithic and Bronze Age rock art across Northumberland in northern England is a good example [1], where over 1200 carvings have been inventoried [17,19]. Northumberland motifs usually are found in the open-air on isolated rock outcrops or boulders in the countryside, and range from simple cup-like features to more complex patterns with rings and grooves (Fig. 1). However, micro-environmental exposures around individual panels differ across the region, which we hypothesise differentially influence their physical condition. Such speculation makes sense because present and past environmental factors have been shown to influence the condition of other heritage monuments elsewhere in the world [20–22].

In the case of Northumberland, mid-Holocene woodland landscapes gave way to exposed heathlands over 2000 years ago due to changes in land-use [23]. This shift in vegetative cover appears to have led to altered soil moisture patterns (fluctuating watertables were replaced by more consistently waterlogged conditions and less vegetative water demand) and increased wind exposures. In contrast, rock art panels are present as fixed points in a dynamic landscape, but their present condition still is the product of past climates and their future condition depends on environmental change [24,25]. However, despite broad climate variations, often it is the very local environment (e.g., soil chemistry, panel orientation, animal impacts) that has a greater influence on the physical condition of individual stones and panels [20,22]. Clearly, factors that affect the relative deterioration of rock art panels are complex across spatial scales as well as over time; therefore, past, present, and future environmental conditions must be considered to develop appropriate strategies for site management.

In order to understand rock art condition, one must first recognise the array of environmental stresses that influence stone deterioration and weathering [26–29], and also acknowledge that different rock types respond to stresses differently [5]. Stone weathering is not a simple process and stresses vary. For example [30], diurnal heating and cooling events cause low magnitude, high frequency stresses. Whereas, freeze/thaw cycling can cause high magnitude, low frequency stresses due to expansion and

contraction of water and ice in rock micropores. Further, air pollution can accelerate rates of stone deterioration in urban settings [31]. Although the scale of stress differs, diurnal and freeze/thaw events, and air pollution can weaken the stone, making it more susceptible to other stresses, such as physical weathering due to wind or saltwater intrusion that disturbs the fabric of the stone.

An appreciation of such issues is key to developing informed rock art management strategies. However, we can only measure contemporary conditions at existing sites, and we must determine the usefulness of this information to relative to long-term preservation. As such, our approach was to measure 27 ambient geochemical and physical descriptors around 18 individual open-air rock art panels with different levels of deterioration to identify specific environment descriptors that correlate with higher levels of rock art deterioration. We then contrasted past and present climatic conditions in the region and assessed how descriptors that correlate with stone deterioration might be effected by environmental change (using UKCP09 [32]). Ultimately, our aim was to develop science-informed strategies for preserving open-air rock art into the near and distant future.

3. Materials and methods

3.1. Rock art panels locations

Two field locations with different types and arrays of open-air rock art panels were chosen for comparison in the study (Fig. 1). Both locations are in areas dominated by Fell Sandstone, with stone type being very consistent among all panels assessed. Fell Sandstone is from Lower Carboniferous age (350–320 Ma) and is composed of fine to medium-grained quartzitic sandstone with some cross-bedding and occasional conglomerate bands [33].

The first location, Lordenshaw, is situated south of Rothbury in north central Northumberland. The panel area crosses a series of hills near an Iron Age ‘hill fort’, which was reused as a Romano-British settlement [16]. Lordenshaw lies within Northumberland National Park and is visited frequently by walkers and tourists. Lordenshaw has over 100 panels with eight panels chosen for study here based on the novelty of motif, their physical location, and the relative prominence of each site. The second field location is known as Weetwood Moor and is ~30 km north of Lordenshaw near the town of Wooler. This location is less visible from local roads and has had less human contact. Ten panels were selected at Weetwood, using similar criteria for panel selection at Lordenshaw.

The names and exact locations of the 18 panels are summarised in Table S1 (see Supplemental Information; SI). With the exception of one panel at Weetwood Moor (Weetwood Moor 6), all 18 panels are in open heathland, and recently have been exposed to grazing animals, including sheep and occasionally cattle. Pollen evidence indicates that both sites were forested prior to about two thousand years ago [34], but forests were cleared as more intensive agriculture developed. Therefore, both panel locations have been in heathlands for over 2000 years.

3.2. Panel Condition Assessment: application of a revised staging system

Various stone condition assessment methods are available for characterising the level of deterioration of rock art panels. Dorn et al. [3] developed a rock art stability index for assessing stone condition, which is complex and useful. In contrast, a simpler approach was developed for building preservation (UAS method; [35]) that is rooted in triage decisions for identifying the stage (condition) of disease in cancer patients [36]. The UAS method is intentionally simple because it is designed for non-experts and volunteers. Given

Table 1
Description of the extent of intervention required for each stage.

Stage	Extent of intervention required
Stage 1	A panel in this condition would require only localised remedial treatment concentrating on individual motifs. A classification of 1 implies no active intervention is required with only periodic reassessment advised.
Stage 2	Panel specific remedial action may be required, but the extent of intervention should be relatively limited because of the lack of distant involvement within the area boundaries.
Stage 3	Significant intervention will be required because up to 50% of the motif and area show evidence of deterioration. Although apparent deterioration may be severe, appropriate conservation treatment should prolong the life expectancy of the panel.
Stage 4	Serious deterioration affecting > 50% of the panel is evident with distant portions of the panel being mutually affected. Considerable intervention will be needed for stage 4 panels and such panels should be prioritised for management intervention, possibly including palliative approaches.

Modified from Warke et al. [35].

our goal is to produce methods useful to heritage managers, often aided by non-experts, we have opted for the simpler approach. However, the method we employ here has been modified to include ecological factors not in the building model and exclude elements less pertinent to open-air rock art or not measurable in the field.

Our new approach defines panel “stage” according to the condition of the motif (M) itself and stone panel surface area (A) immediately around the motif. We call this the “MA” method, and is based on numerical ratings for M and A (one to four, best to worst condition), which are used to estimate panel stage according to criteria defined in Fig. 2. Methods and criteria are similar to the UAS method for building stone [35]. However, the MA method includes additional factors such as the potential for standing water, human or animal damage, and plant growth in the vicinity of the panel. Also, the spread element of the UAS method has been removed because most open-air panels are isolated from other stones and spread is not pertinent to the large majority of rock art panels.

Implementation of the MA method in this study (to generate stage data for statistical comparisons with other descriptors) was performed by having members of our research team perform independent MA assessments for each panel. Panel-information forms were completed in the field by each person (Fig. S1 in SI) and independent stage estimates were made by each member using Fig. 2 ($n=7$). Individual stage estimates then were pooled and a mean stage value was determined for each panel, which was used for statistical comparisons with the environmental descriptors (see later). For reference, panels rated stage two to four by team members are shown in Fig. 3 and implications of staging values are summarised in Table 1.

3.3. Quantification of geochemical and physical descriptors

Three soil cores to approximately 10 cm depth were collected within 15 to 30 cm of the base of each of the 18 panels to characterise local soil conditions. Care was taken to not negatively impact the integrity of each panel base. The soil cores were homogenised, and then sub-divided and analysed in replicate to quantify soil pH, moisture content, conductivity (used as a surrogate for soil salinity), and extractable cation (K, Na, Ca, Mg, Al, Si) and anion (SO_4 , PO_4 , NO_3 , F, Cl) levels. In addition to the soil analyses, panels were characterised in the field according to their surface slope relative to horizontal (slope); standing height from the local ground surface (height); distance to the closest road/residence; extent of stone surface fractures; evidence of human or animal desecration (e.g.,

scratches); coverage of lichens (in %); and level of plant intrusion near the panel. Each researcher estimated surface fracture, animal impact, and vegetation effects (as values from 0 to 3, ranging from “no influence” to “major influence,” respectively) at the same time as they gathered staging data, and values were used as metrics in subsequent statistical analysis.

3.4. Soil analyses

All soil cores were collected over two days in mid-July 2011, three days after the most recent precipitation event to ensure samples represented similar weather and seasonal conditions. Samples were processed or preserved on the day of sampling, except soil moisture content, which was analysed immediately. After homogenising each core, ~5 g sub-fractions were collected, weighed, and then dried at 103 °C for 24 h [37]. Moisture content was determined gravimetrically. The remaining soil was air-dried for 72 h at room temperature and sieved to greater than 2 mm particle size to remove roots, cobbles, and stones before subsequent geochemical analysis.

For all other parameters, the air-dried soil samples were placed into de-ionised water for different times and dilutions for extraction, according to specifications of each analytical method. For example, a 1:2 soil-water ratio was used to assess soil pH [37]. An amount of 10 g of air-dried soil was combined with 20-mL of de-ionised water and shaken at 120 rpm at room temperature for 1 h. The slurry was filtered using 0.7- μm filter paper and pH was quantified on the filtrate using a Jenway 3310 pH meter (Bibby Scientific Ltd), which also was used to estimate soil salinity via electrical conductivity (EC). Salinity was calculated as follows: salinity (mg/L) = $640 \times \text{EC}$ (mS/cm) [38].

Exchangeable cations (i.e., K, Na, Ca, Mg) were extracted using a 1:2.5 soil-water ratio, according to Negrín et al. [39]. An amount of 10 g air-dried soil was mixed with 25 mL de-ionised water in centrifuge tubes and resultant slurries were shaken on a reciprocal shaker table at 120 rpm for 30 min at room temperature. The samples then were settled at 4 °C for 24 h and centrifuged for 15 min at $2000 \times g$. The centrate was filtered with 45- μm filter paper and the filtrate was analysed for the metals using Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES). Calibration standards for each element were prepared according to American Public Health Association [40]. From these data, sodium adsorption ratios (SAR) were calculated using the following equation:

$$\text{SAR} = \frac{[\text{Na}^+]}{\sqrt{\frac{[\text{Ca}^{2+}] + [\text{Mg}^{2+}]}{2}}}$$

where cations are provided in milliequivalent units. SAR describes the tendency of moisture to circulate within a soil matrix [41].

Aqua Regia digestion was employed to quantify Al and Si, according to standard methods [42]. Digestions were performed by aggressively mixing 3 g air-dried soil in a mixture of concentrated 21 mL HCl and 7 mL HNO_3 . After allowing the slurry to stand overnight at room temperature, the solution was heated until reflux conditions were reached and retained for 2 h under such conditions. The solution was cooled and filtered using 0.45- μm paper into a 100-mL volumetric flask. An amount of 10 mL of concentrated HNO_3 was added in the filtrate and the volume was brought up to 100 mL using de-ionised water. Metal levels were quantified using ICP-OES against define standards.

Anions were extracted similar to pH, except a 1:10 soil:water ratio was used because of higher anion levels in the soils [43]. An amount of 3 g air-dried soil was combined with 30 mL de-ionised water and allowed to stand in an ultrasonic bath for 30 min, after which filtration was performed using 0.45- μm filters. Anion levels were quantified using ion chromatography with a Dionex ICS-1000

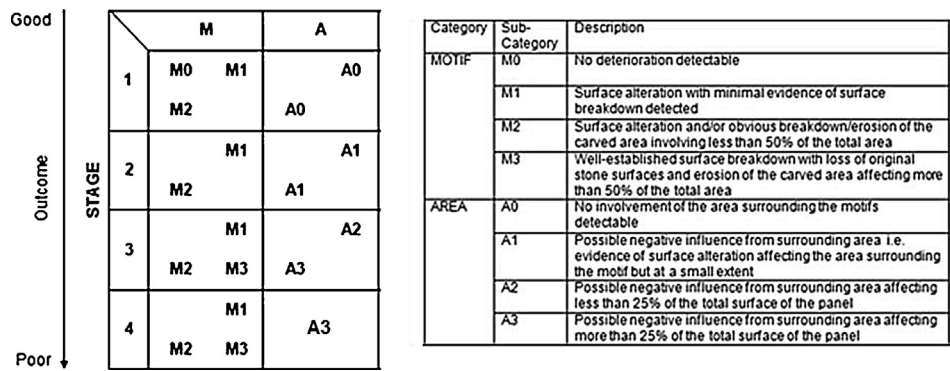


Fig. 2. MA staging system for rock art motifs, areas, and panels.

Modified from the UAS method developed by Warke et al. [35]

and calibrated standards. All cation and anion levels are reported as mg/kg dry-weight of original soil.

3.5. Data processing and statistical analysis

Two types of statistical analysis were performed to compare and contrast relationships between mean stage and geochemical and physical descriptors. First, Pearson's bivariate correlation analysis was performed to observe general relationships among measured parameters. Data always were log-transformed prior to correlation analysis to enhance data normality. Unless otherwise noted, 95% confidence intervals (CI) were used to define significant correlations.

Second, the non-parametric Wilcoxon Rank-Sum test was used to compare geochemical and physical descriptors between panels with higher versus lower stage values. In this analysis, all panels were grouped and ranked according to mean stage (lowest to highest). The panels then were clustered into two sub-groups, representing panels with above and below-mean stage values that were significantly different (Wilcoxon test; $P < 0.01$). We then used the Wilcoxon test to compare the other geochemical and physical descriptors between the high and low stage panel clusters. If significant differences were seen between panel clusters for a given descriptor, it was concluded the descriptor co-varied with stage. The Wilcoxon test also was used to compare descriptors between panels at Lordenshaw versus Weetwood Moor to ensure differences in our low and high stage clusters were not caused by "location".

3.6. Climatic modelling to 2099

Forecasts of future environmental conditions were performed using the UK Climate Projection model, UKCP09 [32]. This model is an evolving tool, which is updated as data become available, and is a key component of climate modelling and projection efforts around the world [44]. The outputs of the model include predicted

precipitation, temperature, humidity, cloud cover, air pressure, and wind patterns for 25-km grid boxes in the UK, which can extend to 2099. Temperature and precipitation were specifically modelled here because these factors are known to strongly influence physiochemical stone weathering rates and mechanisms [45]. UKCP09 also predicts wind speeds, but predictions are less reliable and were used here only for qualitative comparisons.

4. Results and discussion

4.1. Mean stage values and local environmental conditions

The current condition of 18 panels was assessed using the MA method with stage estimates ranging from 2.17 ± 0.13 ($\pm 95\%$ CI) to 3.33 ± 0.12 among panels. The overall mean stage was 2.81 (Table S2 in SI for the complete dataset). If one ranks the 18 panels according to stage, three panels from Lordenshaw and six panels from Weetwood Moor have below-mean stages, whereas five Lordenshaw and four Weetwood Moor panels have above-mean stages. The mean stage for panels at the two locations was not significantly different (2.90 ± 0.14 versus 2.72 ± 0.23 , respectively; $P = 0.161$), implying the relative stage of the panels were not location specific.

To determine how geochemical and physical descriptors correlate with stage, bivariate correlation analysis was performed on all data (Tables S2 and S3 in SI). Only soil Ca ($r = 0.723$, $P = 0.001$), Mg ($r = 0.783$, $P = 0.001$), K ($r = 0.557$, $P = 0.016$), and Na ($r = 0.492$, $P = 0.038$) significantly correlated with stage. Relationships are shown in Fig. 4. These descriptors are all exchangeable cations often associated with soil salinity. Stronger correlations between stage and exchangeable cation levels are observed at Weetwood Moor (Fig. 4), but both locations follow the same trends, especially for soil Ca and Mg.

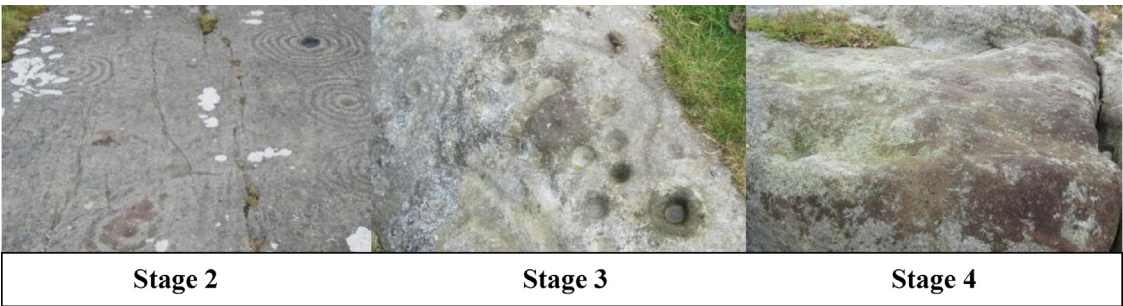


Fig. 3. Examples of panels that reflect different stages of deterioration: stage 2 = Weetwood Moor 3a; stage 3 = West Lordenshaw 1d; stage 4 = Lordenshaw Hillfort 7b.

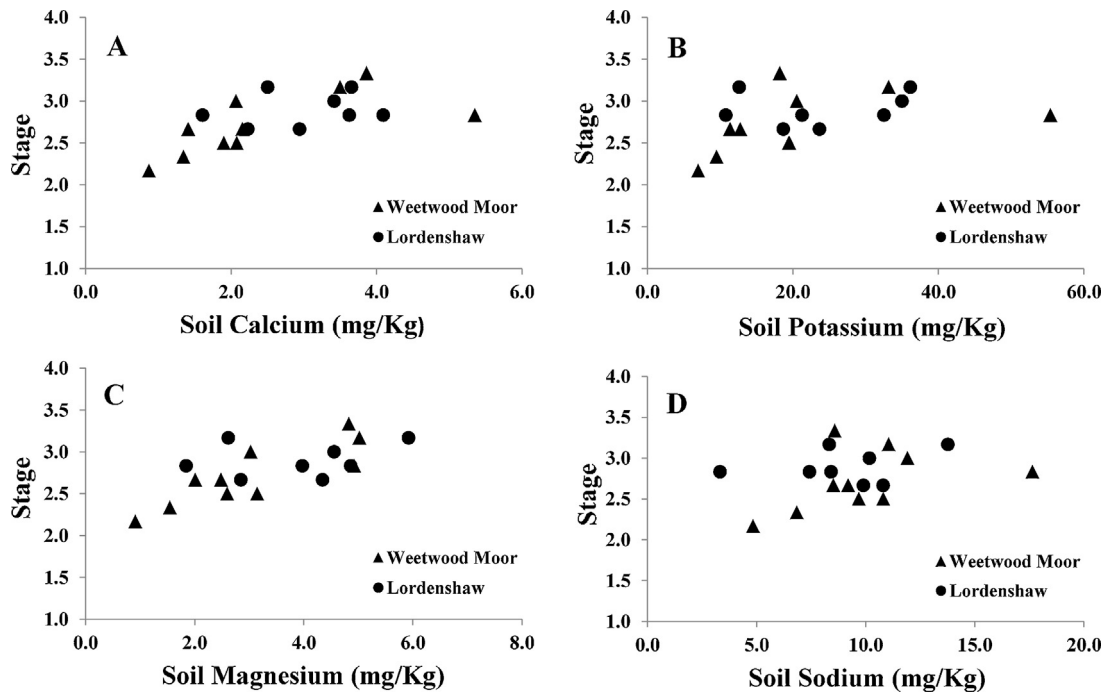


Fig. 4. Relationships between mean stage and exchangeable cation content for (A) calcium, (B) potassium, (C) magnesium, and (D) sodium in soils collected from within 30 cm of the base of each panel.

Interestingly, although actual soil salinity positively trended with stage, the correlation was not statistically significant ($r=0.230$, $P=0.358$), which is likely due to differences in soil moisture (Table S2 and S3). Other factors that showed positive trends with increasing stage were human-animal influence ($r=0.429$, $P=0.076$), soil moisture ($r=0.345$, $P=0.161$), proximity to an active road ($r=0.328$, $P=0.184$), and panel height ($r=0.311$, $P=0.209$). However, data for most parameters were non-normal, which means they are not ideal for bivariate correlation analysis. Therefore, the non-parametric Wilcoxon test was performed on the descriptor data, which were clustered according to high and low mean stage values.

Based on the two-sample test (Table 2), panel height ($P=0.036$), and local soil Ca ($P=0.011$), K ($P=0.021$), and Mg ($P=0.015$) levels were significantly greater for panels with high stage values. Further, elevated soil Na ($P=0.066$) was moderately correlated with high stage panels, and elevated soil moisture ($P=0.214$) and salinity ($P=0.214$) showed weak positive trends with stage. These observations are generally consistent with the bivariate analysis, although

only the two-sample test showed a strong link between stage and panel height. We suspect this is because panel height was measured in 5 cm increments, which made the data highly non-normal and poorly suited to bivariate correlation analysis.

4.2. Current stage and environmental conditions, and past weathering

Statistical analyses show that tall panels in soils with higher levels of exchangeable cations are in poorest physical condition. This suggests that panel deterioration is greatest for panels with most exposure to wind and the potential for chemical intrusion into the stone is more probable. Interestingly, similar factors have been shown to impact building stone decay [30,46,47]. However, our observations primarily have been based on contemporary geochemical and physical data, and the key question is “how meaningful these observations are relative to past weathering, given these panels have existed for thousands of years?” To answer this question, it is necessary to compare contemporary environmental data with suspected exposures over the lifetime of the panels.

4.3. Present and past landscapes and climatic conditions

No wholly reliable record exists that allows one to view the climate of the distant past, although inferential data exist for the last 10,000 years in the form of pollen records and dendrochronology [e.g., 48–50]. Therefore, since the Northumberland panels were carved between about 6000 and 3800 years ago (i.e., during the mid-Holocene), one can roughly deduce temperature, precipitation, and landscape conditions based on proxies. In their review, Briffa and Atkinson [51] suggest changes in air temperature from the mid-Holocene to ~1960 have been small with less than a $\sim 1^\circ\text{C}$ increase in mean temperature over the last 6000 years. They also suggest precipitation has declined slightly over the same period.

However, more reliable data from the past 50 years show very different trends with temperatures, precipitation, and wind speeds

Table 2

Environmental parameters associated with panels that have above-mean stage levels relative to below-mean stage levels.

Correlation with stage	Environmental Parameters
Significantly correlated ($P < 0.05$)	Height ($P=0.036$), Ca ($P=0.011$), K ($P=0.021$), Mg ($P=0.015$)
Moderately correlated ($P < 0.1$)	Na ($P=0.066$)
Weakly correlated ($P < 0.25$)	Moisture ($P=0.214$), salinity ($P=0.214$)
No correlation ($P > 0.25$)	Fracturing ($P=0.373$), lichen ($P=0.0314$), plant intrusion ($P=0.598$), human-animal impact ($P=0.405$), standing water ($P=0.906$), slope ($P=0.340$), proximity to roads ($P=0.511$), proximity to habitation ($P=0.669$), pH ($P=0.260$), SAR ($P=0.340$), Al ($P=0.767$), Si ($P=0.678$), SO_4 ($P=0.314$), PO_4 ($P=0.678$), NO_3 ($P=0.575$), Cl ($P=0.374$), FI ($P=0.906$)

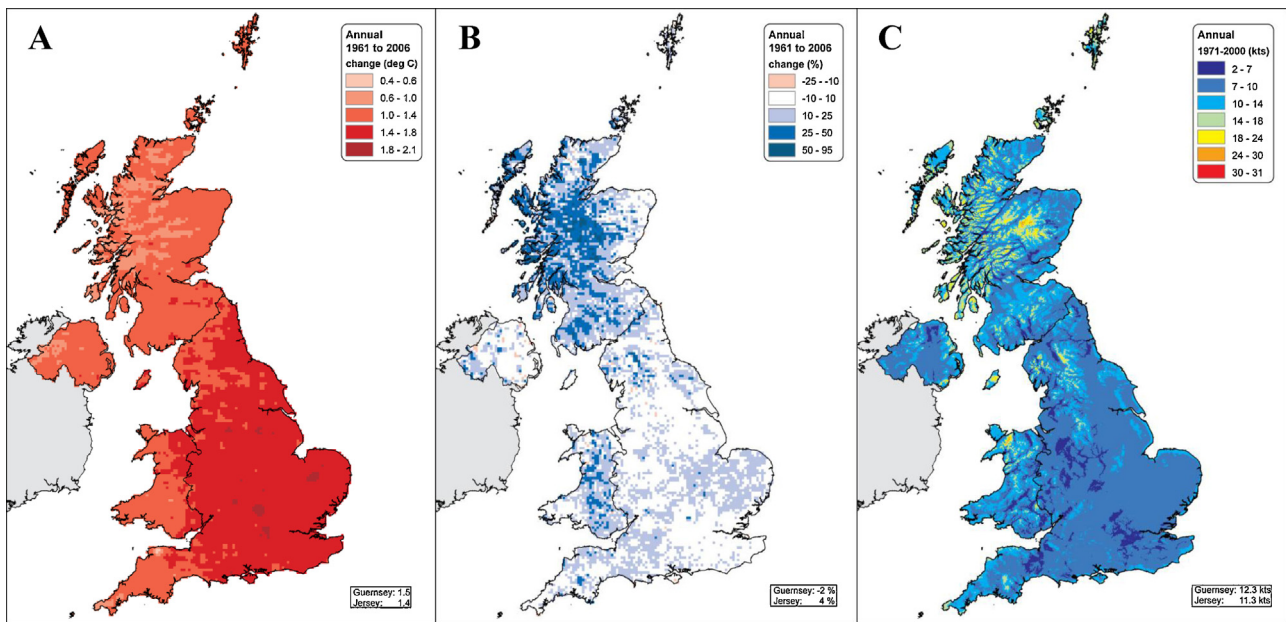


Fig. 5. Changes in (A) mean annual air temperature, (B) mean annual precipitation, and (C) mean annual wind speeds in the UK from 1961 (or 1971) to 2006. Reprinted from DEFRA [32].

becoming more dynamic since 1961 [44]. For example, Fig. 5 shows that mean annual temperature and precipitation levels have increased in Northumberland by about 1.5 °C and 10% since 1961, respectively, and higher winds are more common, which implies that very recent environmental change has been greater than all prior changes since the mid-Holocene. As such, it is not surprising that contemporary environmental descriptors might correlate with the current physical condition of motifs and panels. This does not mean that historic climate variation has not influenced current panel conditions (e.g., mini ice ages or warming periods), but broadly speaking, more change has occurred in the last 50 than the previous 6000 years, and current environmental data are very likely relevant. Although this generalisation may seem simplistic, we suspect we are observing the product of many years of gradual decay, such as growing microfracturing at the stone surface [52], but recent rapid environmental change has triggered significantly increased rates of deterioration [53]. This is consistent with contemporary weathering theory and mechanisms [9].

General climatic descriptions and empirical weathering observations can be used to place current conditions into a grander context. Peltier [45] produced a series of descriptive relationships among local air temperatures, precipitation conditions, and expected weathering mechanisms, which allow crude comparisons between weathering under past and future climate conditions (Fig. 6). Although Peltier lacks modern mechanistic detail, it provides a platform for discussing weathering tendencies under different atmospheric energy conditions and dynamics. Relative to Northumberland, the mean annual air temperatures at Lordenshaw and Weetwood Moor were 9.1 °C and 9.2 °C in 2010, respectively, whereas annual rainfall was 747 mm and 682 mm [32]. If one plots these data on the Peltier diagram (Fig. 6), moderate chemical weathering is predicted based on current conditions, which is not drastically different than the mid-Holocene when the panels were carved (assuming ~1 °C lower temperatures relative to ~1961). A similar observation can be made between 1961 and 2010 where a 1.5 °C shift has been observed. In both cases, Fig. 6 implies moderate chemical weathering, although the rate of stone weathering may be increasing, especially since 1961.

4.4. Future climate forecasting

Data imply that air temperatures and precipitation broadly are increasing in northern locations (e.g., UK), and seasonal and inter-annual variations are becoming more acute [32,44]. Given the trends shown in Fig. 5, the UKCP09 numerical model was used to forecast possible climatic conditions over the next 100 years. Although predictions from such models are highly dependent on assumed human behaviour, they enable us to screen “worst-case”

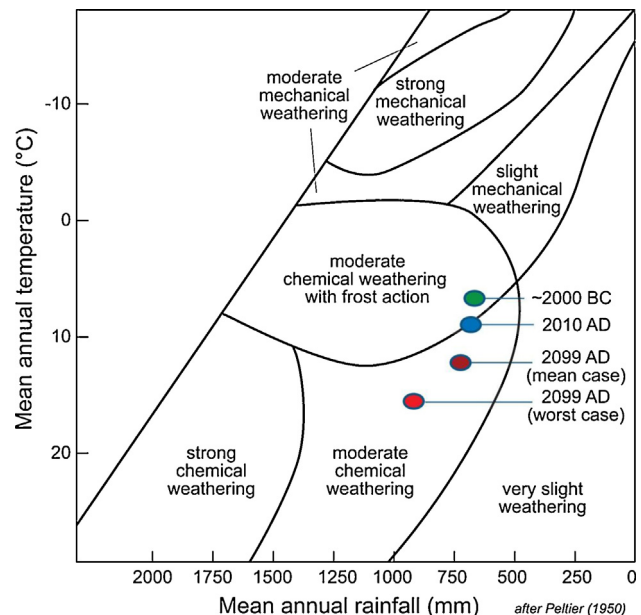


Fig. 6. Diagram showing empirical relationships between mean annual air temperature and precipitation, and primary mechanisms and intensities of stone weathering (revised from [45]). Annotations show past (green), current (blue), mean future (dark red), and “worst-case” future (bright red) case climatic conditions at Lordenshaw and Weetwood Moor (averaged between sites).

scenarios relative to temperature, precipitation, and winds to guide how climate change might impact stone deterioration.

UKCP09 was used to model 25 km² areas surrounding Lordenshaw and Weetwood Moor, and Fig. S2 (SI) provides modelled changes in air temperature and precipitation to 2099. The model projects mean air temperatures will increase from the present to 2099 by +2.9 °C and +2.8 °C for Lordenshaw and Weetwood Moor, respectively, which indicates air temperatures of 12.0 °C and 12.1 °C at the two locations. UKCP09 also predicts increases in precipitation of +0.83% and +1% for Lordenshaw and Weetwood Moor, which suggest mean precipitation levels will be 755 mm and 690 mm in 2099, respectively.

Although these changes seem small, if one compares recent and future changes in temperature conditions with assumed changes since the mid-Holocene, ~four times greater environmental change could potentially occur between 1961 and 2099 than occurred in the previous 6000 years. Further, if one considers the “worst-case” modelled scenario of a 6 °C temperature increase by 2099 (Fig. 6 and S2), dramatically different stone weathering conditions might prevail in the near future, especially warmer, wetter, and windier conditions surrounding panels across the countryside. In fact, qualitative comparisons of the physical condition of panels since the 1970s hint that increased weathering may already be occurring.

4.5. Management and preservation strategies

Considerable uncertainty exists on how past, present, and future environmental conditions has or will influence the integrity of open-air rock art panels around the world. Evidence suggests that rates of panel deterioration may be increasing and this study is among the first efforts at identifying specific environmental factors that influence the present and future condition of such panels. This is critical because unless we understand the types of environmental pressure that most impact deterioration, informed management decisions cannot be made and these iconic heritage resources will be lost forever.

Here we show standing panel height and soil exchangeable cation levels around the panels most strongly correlate with current panel condition. One might argue that such contemporary factors are not necessarily relevant to the long-term state of ancient monuments. However, we show such factors may be more consequential in the future if human-induced climate change proceeds. Obviously, our broad societal goal should be to reduce anthropogenic impacts, but international politics are at odds with solutions. As a result, we must assume worst-case scenarios and consider management options for preserving rock art panels into an unknown future. Therefore, our primary objective for site management should be to build resilience into environments around panels to buffer them from potentially rapid environmental change [53].

For example, data show that taller panels in soils with higher levels of exchangeable cations (Fig. 3) are in poorest physical condition, which implies ionic intrusion may be weakening stone surfaces and winds are physically eroding weakened stone (Table 2). Consequently, management approaches should focus on reducing the impact of such exposures, such as improving drainage around the panels (to reduce ion mobility) and neutralizing soil salinity using methods from agriculture. Sheltering from wind also would be beneficial, but clearly would negatively impact the contextual integrity of the rock art. Alternately, more aggressive management approaches are possible, such as artificially coating open-air rock art panels; however, such methods have been disastrous [54] and physically relocating panels can be equally destructive. Therefore, what do we do?

We propose a four-step approach to managing open-air rock art locations. First, more geochemical and physical field data, calibrated to ambient stage, must be collected for different

environments. Although we show significant correlations between stage and environmental descriptors for Northumberland panels, we do not know how these correlations translate to other settings; data essential for refining the MA method. As an example, we will modify our current MA method to more strongly emphasise panel height for future use with non-experts. Additionally, more data are needed on soil moisture, which is important to all stone weathering [22], but requires a larger field program than was performed here. However, by gaining more data specific to rock art, we can further validate the MA method and extend its use with greater confidence.

Second, we need to study specific weathering mechanisms and the stone itself in more detail. This current study primarily focused on conditions around the panels because rock art stone in Northumberland is relatively homogenous (e.g., sandstones, feldspars). However, studies on other stone types are needed, which are region specific and subject to highly non-linear and complex weathering reactions [9]. Although we feel management strategies should focus on making areas around panels more resilient to environmental change, knowing how different stone types respond to possible interventions is essential to protect stones in other contexts. Third, we need to prioritize rock art panels for immediate attention. Management resources are always limited and we must have a consistent method of choosing panels for intervention. This will be aided by refining the MA method, but also must consider the uniqueness of specific panels; i.e., if we can only save a few panels, which ones do we chose and how do we promote their preservation?

Finally, integrated rock art management strategies should be developed, which should include environment and stone-specific data, a refined MA method and prioritization of sites for intervention. However, it also must include increased awareness and education. Our results show there is a distinct possibility open-air rock art will disappear as our environment changes unless interventions occur soon. Therefore, it has become urgent that decision-makers be made aware of the pending problem; i.e., rock art is not immutable. The scientific groundwork presented here is a good first step, but more work is clearly needed to inform and empower heritage managers to preserve rock art locations into the future.

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Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.culher.2013.01.013>.

References

- [1] Kate Sharpe, Tertia Barnett, Sara Rushton, England's Rock Art: the prehistoric rock art of England: recording, managing and enjoying our carved heritage, English Heritage, England, 2008.
- [2] J. Clottes, L'Art Rupestre – Rock Art. A Universal Cultural Message, UNESCO, Paris, 1997.
- [3] R.I. Dorn, D.S. Whitley, N.V. Cervený, S. Gordon, D.A. Casey, E. Gutbrod, The Rock Art Stability Index, Heritage Management 1 (1) (2008) 35–70.
- [4] J. Curran, P.A. Warke, D. Stelfox, B.J. Smith, Savage F.J., Stone by Stone: A Guide to Building Stone in the Northern Ireland Environment, Appletree Press, Belfast, 2010.

- [5] G.R. Bednarik, The use of weathering indices in rock art science and archaeology, *Rock Art Science* 29 (2012) 59–84.
- [6] P. Brimblecombe, C.M. Grossi, H. Ian, Climate Change Critical to Cultural Heritage, in: Gökçekus H., Türker U., LaMoreaux J.W. (Eds.), *Survival and Sustainability Environmental Earth Sciences*, Part 2, Springer-Verlag, Berlin, 2011, pp. 195–205.
- [7] A. Gómez-Bolea, E. Llopb, X. Ariñob, C. Saiz-Jimenez, A. Bonazzad, P. Messinad, et al., Mapping the impact of climate change on biomass accumulation on stone, *J Cult Heritage* 13 (2012) 254–258.
- [8] A.J. Howard, Managing global heritage in the face of future climate change: the importance of understanding geological and geomorphological processes and hazards, *Int. J. Heritage Stud.* (2012) 1–27.
- [9] A.H. Viles, Implications of future climate change for stone deterioration, 205, Geological Society, Special Publications, London, 2002 [p. 407–18].
- [10] E. Doehne, A.C. Price, *Stone Conservation: an overview of current research*, 2nd ed., J. Paul Getty Trust, Los Angeles, 2010.
- [11] M. Eneko Iriarte, A. Sánchez, A. Foyo, C. Tomillo, Geological risk assessment for cultural heritage conservation in karstic caves, *J. Cult. Heritage* 11 (2010) 250–258.
- [12] Janette Deacon, Rock art and hunter-gatherer communities in relation to World Heritage, in: *World Heritage Centre: Human Evolution: Adaptations, Dispersals and Social Developments (HEADS) World Heritage Thematic Programme*, World Heritage Papers 29, UNESCO – World Heritage Centre, 2011, pp 145–166.
- [13] S.D. Whitley, *Introduction to rock art research*, Left Coast Press, Walnut Creek, CA, 2005.
- [14] P.G. Bahn, *Prehistoric rock art: polemics and progress*, Cambridge University Press, New York, 2010.
- [15] C. Chippendale, G. Nash, *European landscapes of rock art*, Routledge, London, 2002.
- [16] S. Beckensall, *Prehistoric rock art in Northumberland*, Tempus, Stroud, 2001.
- [17] A.D. Mazel, G. Nash, C. Waddington, Art as metaphor: the prehistoric rock-art of Britain, *Archaeopress*, Oxford, 2007.
- [18] L. St Clair, M.R.D. Seaward, *Biodeterioration of stone surfaces*, Kluwer Academic Press, Dordrecht, 2004.
- [19] Stan Beckensall, *Northumberland Rock Art*, Web Access to the Beckensall Archive 2004, available on <http://rockart.ncl.ac.uk/> [Accessed 05 October 2012].
- [20] F. Delalieu, C. Cardella, V. Todorov, V. Dekov, R. Van Grieken, Environmental conditions controlling the chemical weathering of the Madara Horseman monument NE Bulgaria, *J. Cult. Heritage* 2 (2001) 43–54.
- [21] C.H. Lee, Y.H. Jo, J. Kim, Damage evaluation and conservation treatment of the tenth century Korean rock-carved Buddha statues, *Environ. Earth Sci.* 64 (1) (2011) 1–14.
- [22] B.J. Smith, S. McCabe, D. McAllister, C. Adamson, H.A. Viles, J. Curran, A commentary on climate change, stone decay dynamics and the “greening” of natural stone buildings: new perspectives on “deep wetting”, *Environ. Earth Sci.* 63 (7–8) (2011) 1691–1700.
- [23] D. Yeloff, Geel Bas van, P. Broekens, J. Bakker, D. Mauquoy, Mid- to late-Holocene vegetation and land-use history in the Hadrian's Wall region of northern England: the record from Butterburn Flow, *Holocene* 17 (2007) 527–538.
- [24] R.S. Loarie, P.B. Duffy, H. Hamilton, G. Asner, C.B. Field, D.D. Ackerly, The velocity of climate change, *Nature* 462 (2009) 1052–1055.
- [25] D.D. Zhanga, F.H. Lee, Cong Wang, Baosheng Li, Qing Pei, Jane Zhang, and Yulun An, The causality analysis of climate change and large-scale human crisis, *Proc. Natl Acad. Sci.* 108 (2011) 17296–17301.
- [26] J. Bernard, Smith, Scale problems in the interpretation of urban stone decay, in: J. Bernard, Smith, A. Patricia, Warke (Eds.), *Processes of Urban Stone Decay*, Donhead Publishing, Shaftsbury, 1996, pp. 3–18.
- [27] P.A. Warke, J. McKinley, B.J. Smith, Variable weathering response in sandstone: factors controlling decay sequences, *Earth Surf. Proc. Land.* 31 (2006) 715–735.
- [28] P.A. Warke, Complex weathering in drylands: implications of stress history for rock debris breakdown and sediment release, *Geomorphology* 85 (2007) 30–48.
- [29] C. Varotsos, C. Tzanis, A. Cracknell, The enhanced deterioration of the cultural heritage monuments due to air pollution, *Environ. Sci. Pollut. Res.* 16 (2009) 590–592.
- [30] S. McCabe, B.J. Smith, P.A. Warke, Exploitation of inherited weakness in fire-damaged building sandstone: the fatiguing of shocked stone, *Eng. Geol.* 115 (2010) 217–225.
- [31] C. Chris Tzanis, M. Varotsos, J. Ferm, M.N. Christodoulakis, C. Assimakopoulos, Efthymiou, Nitric acid and particulate matter measurements at Athens, Greece, in connection with corrosion studies, *Atm. Chem. Phys.* 9 (2009) 8309–8316.
- [32] Department for Environment, Food and Rural Affairs (DEFRA), UK Climate Projection, 2010, available on <http://ukclimateprojections.defra.gov.uk>. [Accessed 04 October 2012].
- [33] G.J. Mullan, Caves in the Fell Sandstone of Northumberland, *Proc. Univ. Bristol Speleological Soc.* 18 (3) (1989) 430–437.
- [34] Clive Waddington, Dave Passmore, *Ancient Northumberland*, Countrystore, Wooler, 2004.
- [35] P.A. Warke, J.M. Curran, A.V. Turkington, B.J. Smith, Condition Assessment for Building Stone Conservation: A Staging System Approach, *Build. Environ.* 38 (2003) 1113–1123.
- [36] P. Hermanek, O. Scheibe, B. Spiessl, G. Wagner, *TNM Classification of Malignant Tumours*, Springer-Verlag, Berlin, 1987.
- [37] K. Tan, *Soil Sampling, Preparation and Analysis*, 2nd ed., Taylor & Francis Group, London, 2005.
- [38] Y.P. Kalra and D.G. Maynard, *Methods Manual for Forest Soil and Plant Analysis*, Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta, Information Report NOR-X-319E, 1; 1991.
- [39] M.A. Negrín, M. Espino-Mesa, J.M. Hernández-Moreno, Effect of Water: Soil Ratio on Phosphate Release: P, Aluminium and Fulvic Acids Associations in Water Extracts from Andisols and Andic Soils, *Eur. J. Soil Sci.* 47 (3) (1996) 385–393.
- [40] American Public Health Association, *Standard Methods for the Examination of Water and Wastewater*, American Public Health Association, Washington D.C., 1999.
- [41] H.L. Bohn, B.L. McNeal, G.A. O'Connor, *Soil Chemistry*, 3rd ed., John Wiley & Sons, Inc, New York, 2001.
- [42] International Standard Organisation, *Soil Quality – Chemical Methods – Extraction of Trace Elements Soluble in Aqua Regia*, ISO 11466, 1995.
- [43] Dionex Corporation, *Determination of Inorganic Anions in Wastewater by Ion Chromatography*, Application Note 135, 2001.
- [44] Intergovernmental Panel on Climate Change, *Climate Change 2007: The Physical Science Basis Working group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, 2007.
- [45] L. Peltier, Geographic cycle in periglacial regions as it is related to climatic for geomorphology, *Ann. Assoc. Am. Geogr.* 40 (3) (1950) 214–236.
- [46] B.J. Smith, P.A. Warke, Controls and uncertainties in the weathering environment, in: D.S.G. Thomas (Ed.), *Arid Zone Geomorphology*, 2nd ed., J. Wiley & Sons, Chichester, 1997, pp. 41–54.
- [47] J. Bernard, Smith, Diagnosing decay, the nature of stone weathering, in: C. Curran, P.A. Warke, D. Stelfox, J. Bernard, B.J. Smith, J. Savage (Eds.), *Stone by Stone: A Guide to Building Stone in the Northern Ireland Environment*, Appletree Press, Belfast, 2010, pp. 41–72.
- [48] J.R. Pilcher, *Archaeology, palaeoecology and ¹⁴C dating of the Beaghmore stone circle site*, *Ulster J. Archaeol.* 32 (1969) 73–91.
- [49] J.R. Pilcher, A.G. Smith, G.W. Pearson, A. Crowder, Land clearance in the Irish Neolithic: new evidence and interpretation, *Science* 172 (1971) 560–562.
- [50] M.G.L. Baillie, *Tree-Ring Dating and Archaeology*, Croom-Helm, London, 1982.
- [51] K. Briffa, T. Atkinson, *Reconstructing Late-Glacial and Holocene Climates*, in: M. Hulme, E. Barrow (Eds.), *Climates of the British Isles: Present, Past and Future*, Routledge, London, 1997.
- [52] P.A. Warke, Micro-environmental conditions and rock weathering in hot arid regions, *Zeitschrift für Geomorphologie* 120 (2000) 83–95.
- [53] M.J. Giesen, A.D. Mazel, D.W. Graham, P.A. Warke, Care and Management of Ancient Stone Monuments during Environmental Change, *Int. J. Heritage Sust. Dev.* 1 (1) (2011) 60–71.
- [54] S. Bakkevig, Rock art preservation: improved and ecology-based methods can give weathered sites prolonged life, *Norwegian Archaeol. Rev.* 37 (2004) 65–81.